The Electron Ion Collider

Abhay Deshpande

Lecture 1 of 2
Overview of these lectures

- Extensive discussion of JLab6 and Jlab12 – Rolf Ent in the 1st week

Lecture 1: Past and current studies in QCD
- Brief History: The Standard Model & experimental methods (mostly reminders)
- Problems in QCD discovered, but not solved!
  - Spin: **EMC) spin crisis**: inclusive and semi-inclusive DIS and current status
  - Nuclei: Another **puzzle (EMC effect)** and its current status and experimental difficulties
  - **Polarized** Relativistic Heavy Ion Collier: Gluon Spin measurement
  - The transverse spin puzzle: neglected clues **another lesson to keep in mind**

Lecture 2: The US Electron Ion Collider: Frontiers in investigations of QCD
- Solving the spin puzzle: **3D imaging** of the nucleon
- Partons in nuclei: how they **organize**, and **build** nuclei, do they **saturate**?
- Designing an EIC detector and integration in to the Interaction Region (IR)
- EIC: Status and prospects
Beginning of experimental particle/nuclear physics?

The “mother” of all scattering experiments

α-source

gold foil

scintillating screen

Rutherford
\[ \lambda = \frac{h}{2\pi} \cdot \frac{1}{p} \quad \longrightarrow \quad \text{resolution} = \frac{h}{2\pi} \cdot \frac{1}{\text{momentum}} \]
Studying smaller and smaller things…

Fixed Target Particle
Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

SLAC, EMC, NMC, E665, BCDMS, HERMES, JLab, COMPASS, …
Probing matter with electrons…

• In the 1960s Experiments at Stanford Linear Accelerator Center (SLAC) established the quark model and our modern view of particle physics “the Standard Model”

Scattered electron is deflected by a known $B$-field and a fixed vertical angle:

determine $E'$

Spectrometer can rotate in the horizontal plane,

vary $\theta$
The Static Quark Model

Quarks: spin 1/2 fermions, color charge

Baryons: 

Mesons: 

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<th>Quark</th>
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M. Gell-Mann, K. Nishijima (> 1964)
The Static ( Constituent) Quark Model

Quarks: spin 1/2 fermions, color charge

Baryons:

Mesons:

Eight-fold Way:
Account for every hadron we found so far

M. Gell-Mann, K. Nishijima (> 1964)
For detailed properties of the multiquark systems the model failed

How come? What was missing?
Quantum Electrodynamics (QED)

Theory of electromagnetic interactions

- Exchange particles (photons) do not carry electric charge
- Flux is not confined: $V(r) \sim 1/r$, $F(r) \sim 1/r^2$

Recall: Quantum Electrodynamic Theory of electromagnetic interactions

Example Feynman Diagram:
\begin{itemize}
  \item $e^+e^- \text{ annihilation}$
\end{itemize}

Coupling constant ($\alpha$): Interaction Strength

In QED: $\alpha_{em} = 1/137$
Quantum Chromodynamics is the “nearly perfect” fundamental theory of the strong interactions

F. Wilczek, hep-ph/9907340

- Three color charges: red, green and blue

- Exchange particles (gluons) carry color charge and can self-interact

- Flux is confined:

\[ V(r) = -\frac{4\alpha_s}{3} \frac{\alpha_s}{r} + kr \]

\(~1/r\) at short range \(\text{long range} \sim r\)

Long range aspect ⇒ quark confinement and existence of nucleons
Gluons!

Discovery of gluons: Mark-J, Tasso, Pluto, Jade experiments at PETRA (e+e- collider) at DESY (CM energy 13-32 GeV)

- $e^+ e^- \rightarrow q \bar{q} \rightarrow 2$-jets
- $e^+ e^- \rightarrow q \bar{q} g \rightarrow 3$-jets
Standard Model (SM) of physics: Fundamental building blocks

18 Nobel Prizes since 1950

-1

-1/3

0

+2/3

1968: SLAC

1973: CERN

1956: Brookhaven & SLAC

1958: SLAC

1977: Fermilab

1957: Savannah River Plant

1977: CERN

1970: Brookhaven

1971: Caltech and Harvard

1976: SLAC

1947: Manchester University

1974: Washington University

1957: Manchester University

1975: Fermilab

1958: SLAC

1973: CERN

u

c
	

\text{up quark}

c\text{charm quark}

t\text{top quark}

g\text{gluon}

\text{H}\text{BOSON}

\text{Einstein gravity}

\text{Gravitational waves}

\text{Electron neutrino}

\text{Muon neutrino}

\text{Tau neutrino}

\text{Electron}

\text{Muon}

\text{Tau}

\text{Z boson}

\text{W boson}

\text{Photon}

\text{H}\text{boson}
Difficulties in understanding our universe

- Up quark (u)
- Charm quark (c)
- Top quark (t)
- Gluon (g)
- Down quark (d)
- Strange quark (s)
- Bottom quark (b)
- Photon (γ)

- Electron neutrino (νₑ)
- Muon neutrino (νₘ)
- Tau neutrino (νₜ)
- W boson (W)
- Z boson (Z)

Absorption length ≈ 10 light years
Hardly interact with matter
Not detectable
Unstable
Deep Inelastic Scattering (DIS)
Scattering of protons on protons is like colliding Swiss watches to find out how they are build.

R. Feynman

We can ask: What is in there, but not how they are built or how they work!
Study of internal structure of a watermelon:

A-A (RHIC/LHC)
1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)
Deep Inelastic Scattering

\[ q = \frac{h}{\lambda} \]

\( h = \text{constant} \)
\( \lambda = \text{wavelength} \)
\( q = \text{momentum transferred} \)

Deep Inelastic: \((\lambda \ll \text{Proton Size})\)
Deep Inelastic Scattering: Precision & Control

**Kinematics:**

\[ s = 4E_e E_p \]

**Inclusive events:** \( e+p/A \rightarrow e'+X \)

**Semi-Inclusive events:** \( e+p/A \rightarrow e'+h(\pi,K,p,\text{jet})+X \)

**Exclusive events:** \( e+p/A \rightarrow e'+p'/A'+h(\pi,K,p,\text{jet}) \)
What does a proton look like in transverse dimension?

Bag Model: Gluon field distribution is wider than the fast moving quarks. Color (Gluon) radius > Charge (quark) Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks. Color (Gluon) radius ~ Charge (quark) Radius

Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks: Color (Gluon) radius < Charge (quark) Radius

Need transverse images of the quarks and gluons in protons
What do **gluons** in protons look like?

Unpolarized & polarized parton distribution functions

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**Need to go beyond 1-dimension!**

**Need (2+1)D image of gluons in a nucleon in position & momentum space**
How does a Proton look at low and very high energy?

**Low energy: High x**
Regime of fixed target exp.

**High energy: Low- x**
Regime of a Collider

Cartoon of boosted proton

**At high energy:**
- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a *runaway growth?*
Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

“...The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud....”

F. Wilczek, in “Origin of Mass”
Nobel Prize, 2004
Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

Apparent “indefinite rise” in gluon distribution in proton!

What could limit this indefinite rise? ➔ saturation of soft gluon densities via $gg \rightarrow g$ recombination must be responsible.

Where? No one has unambiguously seen this before!
If true, effective theory of this ➔ “Color Glass Condensate”
Emergent Dynamics in QCD

*Without gluons, there would be no nucleons, no atomic nuclei... no visible world!*

- Massless gluons & almost massless quarks, *through their interactions*, generate most of the mass of the nucleons
- Gluons carry ~50% of the nucleon's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

Experimental insight and guidance crucial for complete understanding of how hadrons & nuclei emerge from quarks and gluons
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter.

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties emerge from them and their interactions?

How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?
The Electron Ion Collider

For e-N collisions at the EIC:
- Polarized beams: e, p, d/³He
- e beam 5-10(20) GeV
- Luminosity $L_{ep} \sim 10^{33-34}$ cm$^{-2}$sec$^{-1}$
- 100-1000 times HERA
- 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:
- Wide range in nuclei
- Luminosity per nucleon same as e-p
- Variable center of mass energy

World’s first
Polarized electron-proton/light ion and electron-Nucleus collider

Both designs use DOE’s significant investments in infrastructure
Spin an important tool to understand nature....
Levitating top

Despite understanding gravity, and rotational motion individually, when combined it produces unexpected, unusual and interesting results.

In nature, we observe such things and try to understand the physics behind it.
1955
Bohr & Pauli
Trying to understand
The tippy top toy
1900’s a Century of Spin Surprises!
Experiments that fundamentally changed the way we think about physics!

• Stern Gerlach Experiment (1921)
  • Space quantization associated with direction
• Goudsmit and Uhlenbeck (1926)
  • Atomic fine structure and electron spin
• Stern (1933)
  • Proton’s anomalous magnetic moment: 2.79 (proton not a point particle)
• Kusch (1947)
  • Electron’s anomalous magnetic moment: 1.00119 (electron a point particle)
• Yale-SLAC Experiment (Prescott et al.)
  • Electroweak interference in polarized e-D scattering
• European Muon Collaboration (EMC) (1988)
  • The Nucleon Spin Crisis (now – a puzzle)
20th Century could be called a “Century of Spin Surprises!”

In fact, it has noted by:

Prof. Elliot Leader (University College London) that

“Experiments with spin have killed more theories in physics, than any other single physical variable”

Prof. James D. Bjorken (SLAC), jokingly, that

“If theorists had their way, they would ban all experiments involving spin”
Let's get in to details of e-p scattering: what do we learn?
Lepton Nucleon Cross Section:

Assume only $\gamma^*$ exchange

$$\frac{d^3\sigma}{dx dy d\phi} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(k, q, s,) W^{\mu\nu}(P, q, S)$$

- Lepton tensor $L_{\mu\nu}$ affects the kinematics (QED)
- Hadronic tensor $W^{\mu\nu}$ has information about the hadron structure

$$W^{\mu\nu}(P, q, S) = -(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}) F_1(x, Q^2) + (p^\mu - \frac{P \cdot q}{q^2} q^\mu)(p^\nu - \frac{P \cdot q}{q^2} q^\nu) \frac{1}{P \cdot q} F_2(x, Q^2)$$

$$-i\epsilon^{\mu\nu\lambda\sigma} q^\lambda \left[ \frac{M S_\sigma}{P \cdot q} g_1(x, Q^2) + g_2(x, Q^2) - \frac{M (S \cdot q) P_\sigma}{P \cdot q} g_2(x, Q^2) \right]$$
Lepton-nucleon cross section... with spin

\[ \Delta \sigma = \cos \psi \Delta \sigma_\parallel + \sin \psi \cos \phi \Delta \sigma_\perp \]

\[ \gamma = \frac{2Mx}{\sqrt{Q^2}} = \frac{\sqrt{Q^2}}{v}. \]

For high energy scattering \( \gamma \) is small

\[ \frac{d^2 \Delta \sigma_\parallel}{dx dQ^2} = \frac{16 \pi \alpha^2 y}{Q^4} \left[ \left( 1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4} \right) g_1 - \frac{\gamma^2 y}{2} g_2 \right] \]

\[ \frac{d^3 \Delta \sigma_T}{dx dQ^2 d\phi} = -\cos \phi \frac{8 \alpha^2 y}{Q^4} \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1 + g_2 \right) \]
Cross section asymmetries.

- $\Delta\sigma_\parallel$: anti-parallel – parallel spin cross sections
- $\Delta\sigma_{\text{perp}}$: lepton-nucleon spins orthogonal
- Instead of measuring cross sections, it is prudent to measure the differences: Asymmetries in which many measurement imperfections might cancel:

$$A_\parallel = \frac{\Delta\sigma_\parallel}{2\bar{\sigma}}, \quad A_\perp = \frac{\Delta\sigma_\perp}{2\bar{\sigma}},$$

which are related to virtual photon-proton asymmetries $A_1,A_2$:

$$A_\parallel = D(A_1 + \eta A_2), \quad A_\perp = d(A_2 - \xi A_1).$$

\[
\begin{align*}
A_1 &= \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1} \\
A_2 &= \frac{2\sigma^{TL}}{\sigma_{1/2} + \sigma_{3/2}} = \gamma \frac{g_1 + g_2}{F_1}
\end{align*}
\]
• $A_{||}$ could be written down in terms of spin structure function $g_1$, and $A_2$ along with kinematic factors:

$$\frac{A_{||}}{D} = (1 + \gamma^2) \frac{g_1}{F_1} + (\eta - \gamma)A_2$$

Where $A_1$ is bounded by 1, and $A_2$ by $\sqrt{R} = \sigma_T/\sigma_L$, when terms related $A_2$ can be neglected, and $\gamma$ is small,

$$A_1 \approx \frac{A_{||}}{D}, \quad \frac{g_1}{F_1} \approx \frac{1}{1 + \gamma^2} \frac{A_{||}}{D}$$

$$F_1 = \frac{1 + \gamma^2}{2x(1+R)} F_2 \quad A_2 = \frac{1}{1 + \eta \xi} \left( \frac{A_\perp}{d} + \xi \frac{A_{||}}{D} \right)$$
Relation to spin structure function $g_1$

$$g_1(x) = \frac{1}{2} \sum_{i=1}^{n_f} e_i^2 \Delta q_i(x)$$

$$\Delta q_i(x) = q_i^+(x) - q_i^-(x) + \bar{q}_i^+(x) - \bar{q}_i^-(x)$$

- In QCD quarks interact with each other through gluons, which gives rise to a $Q^2$ dependence of structure functions

- At any given $Q^2$ the spin structure function is related to polarized quark & gluon distributions by coefficients $C_q$ and $C_g$
First Moments of SPIN SFs

\[ \Delta q = \int_0^1 \Delta q(x) \, dx \]

\[ g_1(x) = \frac{1}{2} \sum_f e_f^2 \{ q_f^+(x) - q_f^-(x) \} = \frac{1}{2} \sum_f e_f^2 \Delta q_f(x) \]

\[ \Gamma_1^p = \frac{1}{2} \left[ \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right] = \frac{1}{12} (\Delta u - \Delta d) + \frac{1}{36} (\Delta u + \Delta d - 2\Delta s) + \frac{1}{9} (\Delta u + \Delta d + \Delta s) \]

Neutron decay

Hyperon Decay

\[ \Gamma_1^{p,n} = \frac{1}{12} \left[ \pm a_3 + \frac{1}{\sqrt{3}} a_8 \right] + \frac{1}{9} a_0 \]
First moment of $g_1^p(x) :$ Ellis-Jaffe SR

\[ \Gamma_{1,p}^{p,n} = \frac{1}{12} \left[ \pm a_3 + \frac{1}{\sqrt{3}} a_8 \right] + \frac{1}{9} a_0 \]

\[ a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025 \quad a_8 = 3F - D \implies F/D = 0.575 \pm 0.016 \]

Assuming $SU(3)_f \& \Delta s = 0$ , Ellis & Jaffe:

\[ \Gamma_{1,p} = 0.170 \pm 0.004 \]

Measurements were done at SLAC (E80, E130) Experiments:
  Low 8-20 GeV electron beam on fixed target
  Did not reach low enough $x \rightarrow x_{\text{min}} \sim 10^{-2}$
  Found consistency of data and E-J sum rule above
Spin Crisis

Life was easy in the Quark Parton Model until first spin experiments were done!
Experimental Needs in DIS

**Polarized target, polarized beam**

- Polarized targets: hydrogen (p), deuteron (pn), helium ($^3\text{He}: 2\text{p+n}$)
- Polarized beams: electron, muon used in DIS experiments

Determine the kinematics: measure with high accuracy:

- Energy of **incoming lepton**
- Energy, direction of **scattered lepton**: energy, direction
- Good identification of **scattered lepton**

**Control of false asymmetries:**

- Need excellent understanding and control of false asymmetries (time variation of the detector efficiency etc.)
Nucleon’s Spin: Naïve Quark Parton Model (ignoring relativistic effects... now, illustration only, but historically taken seriously)

- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
- And there are three of them in the

\[ S_{\text{proton}} = \text{Sum of all quark spins!} \]

\[
\frac{1}{2} = \frac{1}{2} + \frac{1}{2} + \frac{1}{2} \\
\frac{1}{2} = \frac{1}{2} - \frac{1}{2} + \frac{1}{2}
\]
How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering

\[ A_{\gamma^*p} \propto \frac{N^{\uparrow \downarrow} - N^{\uparrow \uparrow}}{N^{\uparrow \downarrow} + N^{\uparrow \uparrow}} \]

\[ \lambda = \frac{\text{Constant}}{\rho} \]

Spin 1/2 quarks
Experimental issues

Possible sources of false asymmetries:
• beam flux
• target size
• detector size
• detector efficiency
An Ideal Situation

\[ A_{measured} = \frac{N^{\leftrightarrow} - N^{\rightarrow\rightarrow}}{N^{\leftrightarrow} + N^{\rightarrow\rightarrow}} \]

\[ N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff} \]

\[ N^{\leftrightarrow} = N_b \cdot N_t \cdot \sigma^{\leftrightarrow} \cdot D_{acc} \cdot D_{eff} \]

If all other things are equal, they cancel in the ratio and….

\[ A_{measured} = \frac{\sigma^{\leftrightarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\leftrightarrow} + \sigma^{\rightarrow\rightarrow}} \]
A Typical Setup

- Experiment setup (EMC, SMC, COMPASS@CERN)

- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest
Asymmetry Measurement

\[ \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} = A_{\text{measured}} = P_{\text{beam}} \cdot P_{\text{target}} \cdot f \cdot A_{\parallel} \]

- \( f = \) dilution factor proportional to the polarizable nucleons of interest in the target “material” used, for example for \( \text{NH}_3 \), \( f=3/17 \)

\[ g_1 \approx \frac{A_{\parallel}}{D} \cdot F_1 \approx \frac{A_{\parallel}}{D} \frac{F_2}{2 \cdot x} \int_0^1 g_1^p(x, Q_0^2) dx = \Gamma_1^p(Q_0^2) \]

- \( D \) is the depolarization factor, kinematics, polarization transfer from polarized lepton to photon, \( D \sim y^2 \)
Proton Spin Crisis (1989)!

\[ \Delta \Sigma = (0.12) \pm (0.17) \text{ (EMC, 1989)} \]
\[ \Delta \Sigma = 0.58 \text{ expected from E-J sum rule...} \]

If the quarks did not carry the nucleon’s spin, what did? \( \rightarrow \) Gluons?
How significant is this?

“It could the discovery of the century. Depending, of course on how far below it goes…”
Measurement of unpolarized glue at HERA

- Scaling violations of $F_2(x, Q^2)$
  \[ \frac{\partial F_2(x, Q^2)}{\partial \ln Q^2} \propto G(x, Q^2) \]

- NLO pQCD analyses: fits with linear DGLAP* equations

F$_2$ Structure Function

Vs.

Q$^2$ mom. exchanged

* Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

7/15/2019
NNPSS at U. of Tennessee, Lecture 1 of 2 on Electron Ion Collider, Abhay Deshpande
Experiments

- HERMES at DESY
- SMC, COMPASS at CERN

Hall A at Jlab

- high energy beams
- large angular acceptance
- broad kinematical range

variety of tracking detectors:
- Scifi
- Strews
- Silicon
- DC
- Micromegas
- MWPC
- PHGEM
- LDC

to cope with different particle flux from $\theta = 0$ to $\theta = 200$ mrad with a good azimuthal acceptance
QCD fits - World data on $g_1^p$ and $g_1^d$

$\rightarrow g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$x$ and $Q^2$ coverage not yet sufficient for precise $\Delta g$
Can be improved by constraining from pp data (as DSSV, NNPDF...)

\[ \frac{d g_1}{d \ln Q^2} \propto -\Delta g(x, Q^2) \]
Similar to extraction of PDFs at HERA

(RECALL)

NLO pQCD analyses: fits with linear DGLAP* equations

* Dokshitzer, Gribov, Lipatov, Altarelli, Parisi
Large uncertainty in gluon polarization (+/-1.5) results from lack of wide $Q^2$ arm

We need polarized high energy deep inelastic scattering experiment!

We need a polarized e-p collider

So we need to measure scaling violation in the same region

HERA made measurements!
Global analysis of Spin SF

- World’s all available $g_1$ data
- Coefficient and splitting functions in QCD at NLO
- Evolution equations: DGLAP
  \[ f(x) = x^\alpha (1 - x)^{\beta} (1 + ax + bx^2) \]
- Quark distributions fairly well determined, with small uncertainty
  - $\Delta \Sigma = 0.23 \pm 0.04$
- Polarized Gluon distribution has largest uncertainties
  - $\Delta G = 1 \pm 1.5$

ABFR analysis method by SMC PRD 58 112002 (1998)
Consequence:

• Quark + Anti-Quark contribution to nucleon spin is definitely small: Ellis-Jaffe sum violation confirmed
\[ \Delta \Sigma = 0.30 \pm 0.05 \]

• Is this smallness due to some cancellation between quark+anti-quark polarization

• The gluon’s contribution seemed to be large!
\[ \Delta G = 1 \pm 1.5 \]

• Most NLO analyses by theoretical and experimental collaboration consistent with HIGH gluon contribution
  • Direct measurement of gluon spin with other probes warranted. Seeded the RHIC Spin program
We have come a long way, but do we understand nucleon spin?

\[ \Delta \Sigma = 0.12 \pm 0.17 \]
Evidence for transverse spin had been observed but *ignored* for almost 3 decades...
Complementary techniques

Photons colorless: forced to interact at NLO with gluons
Can’t distinguish between quarks and anti-quarks either

Why not use polarized quarks and gluons abundantly available in protons as probes?
RHIC as a Polarized Proton Collider

Without Siberian snakes: $\nu_{sp} = G_\gamma = 1.79$ E/m $\rightarrow \sim 1000$ depolarizing resonances

With Siberian snakes (local $180^\circ$ spin rotators): $\nu_{sp} = \frac{1}{2}$ $\rightarrow$ no first order resonances

Two partial Siberian snakes ($11^\circ$ and $27^\circ$ spin rotators) in AGS
Siberian Snakes

- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist

Courtesy of A. Luccio
Measuring $A_{LL}$

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \quad R = \frac{L_{++}}{L_{+-}}$$

(N) Yield  
(R) Relative Luminosity  
(P) Polarization

- Bunch spin configuration alternates every 106 ns  
- Data for all bunch spin configurations are collected at the same time  
⇒ Possibility for false asymmetries are greatly reduced

Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.
Recent global analysis: DSSV

D. deFlorian et al., arXiv:1404.4293

Wide spread at low $x$ ($x<0.05$) of alternative fits consistent within 90% of C.L.

DSSV: Original global analysis incl. first RHIC results (Run 5/6)
DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates

DSSV - NEW FIT: Strong impact on $g(x)$ with RHIC run 9 results

Positive for $x > 0.05$!

Impact on $g$ from RHIC data

"…better small-$x$ probes are badly needed."

While RHIC made a huge impact on $\Delta G$
large uncertainties to remain in the low-$x$ unmeasured region!

$\Delta G = 0.2 +/- 0.02 +/- 0.5$
Transverse spin introduction

\[ A_N = \frac{N_L - N_R}{N_L + N_R} \]

\[ A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001 \]

- Since people starved to measure effects at high \( p_T \) to interpret them in pQCD frameworks, this was “neglected” as it was expected to be small….. However….

- Pion production in single transverse spin collisions showed us something different….
Pion asymmetries: at most CM energies!

Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well.
Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

Example:

\[ p^\uparrow + p \rightarrow h_1 + h_2 + X \]

\[ SSA_{Collins} \propto \vec{S}_q \cdot (\vec{h}_1 \times \vec{k}_h) \]

Polarization of struck quark which fragments to hadrons.

What does "Sivers effect" probe?

Quarks orbital motion adds/subtracts longitudinal momentum for negative/positive $\hat{x}$.

**Red shift**

Hard probe (Parton, $\gamma^*$)

**Blue shift**

**Final State Interaction** between outgoing quark and target spectator.

**Sivers function**

$$f_{1T}^\perp (x, \vec{k}_q^\perp)$$

**Top view, Breit frame**

**Parton Distribution Functions**

- PRD59 (1999) 014013
- PRD66 (2002) 114005

**Generalized Parton Distribution Functions**

- PRD59 (1999) 014013
- hep-ph/0703176

**Quark Orbital angular momentum**
Lepton nucleus scattering for understanding the nuclear structure and dynamics:

Nuclear structure a known unknown....
PDFs in nuclei are different than in protons!

Since 1980’s we know the ratio of $F_2$’s of nuclei to that of Deuteron (or proton) are different.

Nuclear medium modifies the PDF’s.

Fair understanding of what goes on, in the $x > 0.01$.

However, what happens at low $x$?

Does this ratio saturate? Or keep on going? – Physics would be very different depending on what is observed.

Data needed at low-x
Lessons learned:

• Proton and neutrons are not as easy to understand in terms of quarks, and gluons, as earlier anticipated:
  • Proton’s spin is complex: alignment of quarks, gluons and possibly orbital motion
  • Proton mass: interactions amongst quarks and gluons, not discussed too much

• To fully understand proton structure (including the partonic dynamics) one needs to explore over a much broader x-Q2 range (not in fixed target but in collider experiment)

• e-p more precise than p-p as it probes with more experimental control and precision

• Low-x behavior of gluons in proton intriguing; Precise measurements of gluons critical.

We need a new polarized collider…. 
The Electron Ion Collider

For e-A collisions at the EIC:
- Wide range in nuclei
- Luminosity per nucleon same as e-p
- Variable center of mass energy

For e-N collisions at the EIC:
- Polarized beams: e, p, d/3He
- e beam 5-10(20) GeV
- Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1} 100-1000 times HERA
- 20-100 (140) GeV Variable CoM

The design also needs to allow for the detection of forward scattered protons with a transverse momentum in the range between 0.2 and 1.3 GeV/c. This latter requirement limits the maximum proton angular spread at the collision point in at least one plane.

The outline for the eRHIC (RR) collider is shown in Figure 1. Polarized electron bunches of 10 nC are generated in a state-of-the-art polarized electron source followed by a 400 MeV injector LINAC. Once per second, the bunch is accelerated in a rapid cycling synchrotron in the RHIC tunnel to a beam energy of up to 18 GeV and is then injected into the electron storage ring where it is brought into collisions with the hadron beam. In order to maintain high spin polarization each of the 330 (1320) electron-bunches of 18 GeV (10 GeV) in the storage ring is replaced after 6 (30) minutes of storage. The Figure 2 shows the peak luminosity versus CM energy for the eRHIC design. Table ?? lists the main parameters of the designs for the beam energies with the highest peak luminosity. In case of collisions between electrons and ions, electron-nucleon luminosity of similar levels are achieved as well. The high luminosity is achieved due to ambitious beam-beam parameters, flat shape of the electron and hadron bunches at the collision point, and large circulating electron and proton currents distributed over as many as 1320 bunches (in the case of 10 GeV electron energy). In order to separate the electron and hadron beams shortly after collisions to avoid parasitic crossings the beams collide under a crossing angle of 22 mrad and the crossing angle e^{\text{c}}\text{c}$$^{\text{c}}$$\text{c}$ effects are canceled by employing crab crossing using so-called crab cavities.

The main elements of eRHIC which have to be added to the RHIC complex are:
- A low frequency photocathode gun delivering 10 nC polarized electrons at 1 Hz
- A 400 MeV injector normal conducting S-band linac
- A 18 GeV rapid cycling synchrotron (RCS) in the RHIC tunnel for an initial low cost step, a 10 GeV rapid cycling synchrotron would fit in the AGS tunnel.
- A high intensity, spin-transparent 18 GeV electron storage ring in the RHIC tunnel

Crab crossing was already used to increase the luminosity of the electron-positron collider KEKB, and is planned for the high luminosity upgrade of the proton-proton collider LHC with beam tests planned in the near future.